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Research paper

Subaqueous early eruptive phase of the late Aptian Rajmahal volcanism, India: Evidence from volcaniclastic rocks, bentonite, black shales, and oolite

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A B S T R A C T

The late Aptian (118–115 Ma) continental flood basalts of the Rajmahal Volcanic Province (RVP) are part of the Kerguelen Large Igneous Province, and constitute the uppermost part of the Gondwana Supergroup on the eastern Indian shield margin. The lower one-third of the Rajmahal volcanic succession contains thin layers of plant fossil-rich inter-trappean sedimentary rocks with pyroclasts, bentonite, grey and black shale/mudstone and oolite, whereas the upper two-thirds consist of sub-aerial fine-grained aphyric basalts with no inter-trappean material. At the eastern margin and the north-central sector of the RVP, the volcanics in the lower part include rhyolites and dacites overlain by enstatite-bearing basalts and enstatite-andesites. The pyroclastic rocks are largely felsic in composition, and comprise ignimbrite as well as coarse-grained tuff with lithic clasts, and tuff breccia with bombs, lapilli and ash that indicate explosive eruption of viscous rhyolitic magma. The rhyolites/dacites (>68 wt.%) are separated from the andesites (<60 wt.%) by a gap in silica content indicating their formation through upper crustal anatexis with only heat supplied by the basaltic magma. On the other hand, partially melted siltstone xenoliths in enstatite-bearing basalts suggest that the enstatite-andesites originated through mixing of the upper crust with basaltic magma, crystallizing orthopyroxene at a pressure-temperature of ~3 kb/1150 °C. In contrast, the northwestern sector of the RVP is devoid of felsic-intermediate rocks, and the volcaniclastic rocks are predominantly mafic (basaltic) in composition. Here, the presence of fine-grained tuffs, tuff breccia containing sideromelane shards and quenched texture, welded tuff breccia, peperite, shale/mudstone and oolite substantiates a subaqueous environment. Based on these observations, we conclude that the early phase of Rajmahal volcanism occurred under predominantly subaqueous conditions. The presence of grey and black shale/mudstone in the lower one-third of the succession across the entire Rajmahal basin provides unequivocal evidence of a shallow-marine continental shelf-type environment. Alignment of the Rajmahal eruptive centers with a major N–S mid-Neoproterozoic lineament and the presence of a gravity high on the RVP suggest a tectonic control for the eruption of melts associated with the Kerguelen plume that was active in a post-Gondwana rift between India and Australia-Antarctica.

1. Introduction

Continental flood basalts such as the Deccan (Beane et al., 1986), Paraná (Bellieni et al., 1986), Karoo (Marsh et al., 1997), and Columbia River (Carlson and Hart, 1988) are characterized by massive volumes of predominantly mafic lavas, and subordinate ultramafic (Ghatak and Basu, 2013), silicic (Bell and Emeleus, 1988), and inter-lava sedimentary rocks (Sengupta, 1988). These rocks form in an intraplate tectonic setting and constitute a major part of Large Igneous Provinces (LIPs), which are widely accepted as the product of mantle plumes, emplaced during the break-up of supercontinents (Mahoney and Coffin, 1997; White et al., 2009).

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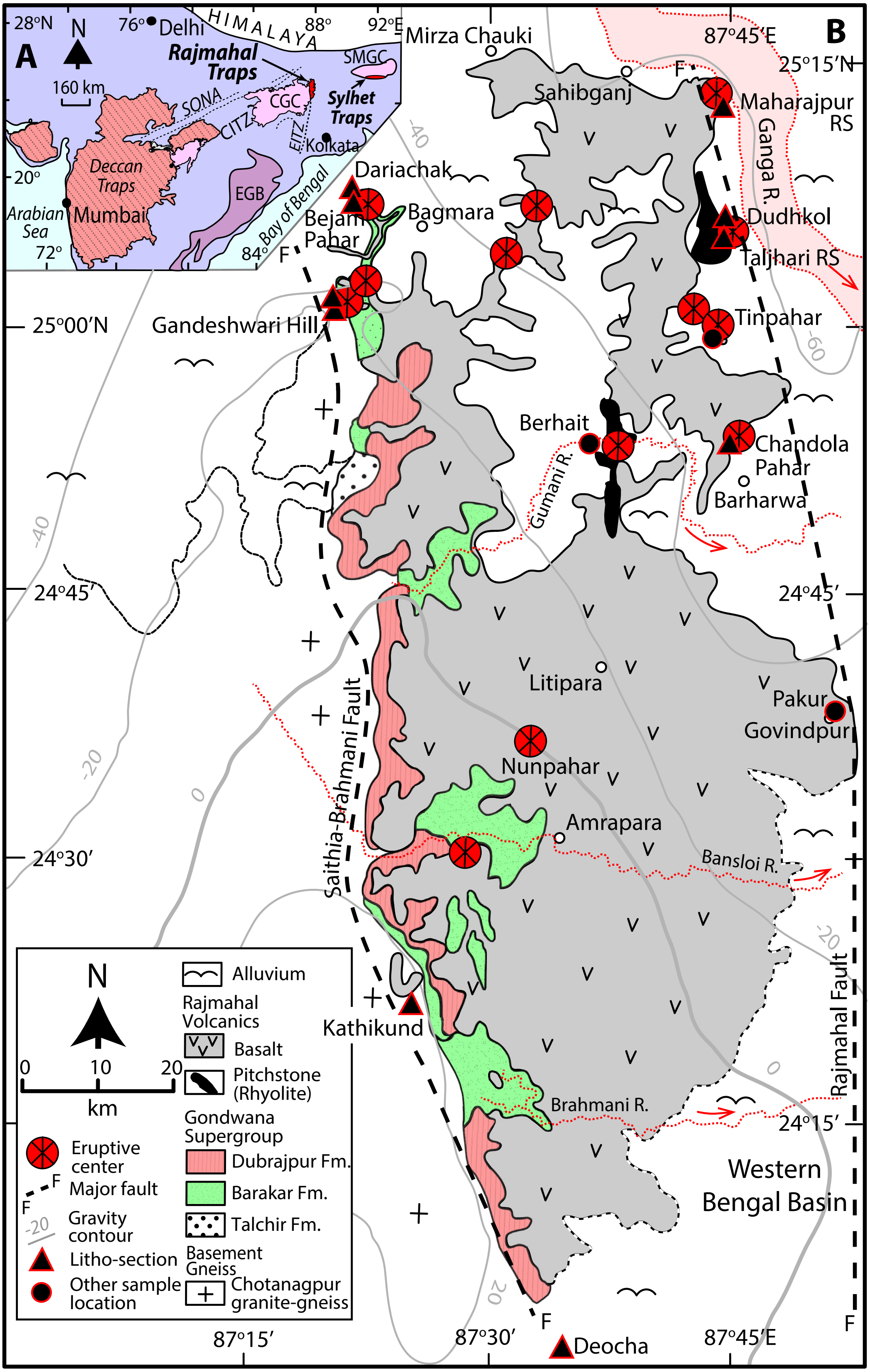

Figure 1. (A) Location of the Rajmahal Volcanic Province (Rajmahal Traps) and prominent geological features on the Indian Shield. CITZ: Central Indian Tectonic Zone; EGB: Eastern Ghats belt; EITZ: Eastern Indian Tectonic Zone; SMGC: Shillong-Meghalaya gneissic complex; SONA: Son-Narmada lineament. (B) Details of the Rajmahal Volcanic Province (after Ghose and Kent, 2003) showing the areal extent of basalts and pitchstones, location of major boundary faults, eruptive centers, lithological sections and samples, and Bouguer gravity contours (−60 to +20 mGal, Singh et al., 2004). RS – Railway Station.

The variety and structures of the lavas and inter-trappean sediments provide clues to the paleo-environment, eruption rates and environmental impact of the eruptions (Keller et al., 2008; Jay and Widdowson, 2008; Bond and Wignall, 2014). The distribution of initial volcanism is controlled largely by pre-existing crustal-lithospheric weaknesses and topography, and by the presence of water bodies (Jerram and Widdowson, 2005). Interaction with upper crustal rocks may produce silicic lavas and consequent explosive pyroclastic eruptions, and effusive sub-aqueous basaltic eruptions may produce hyaloclastites (Bryan et al., 2002). Upper crustal interactions in localized magma chambers may be related to a decrease in the eruption rate that may lead to the development of widely-spaced eruptive centers (Jerram and Widdowson, 2005). A study of the volcaniclastic rocks is thus crucial to understand the eruptive cycles, processes involved in the formation of the magma, and mechanism of formation of continental flood basalt provinces.

The early Cretaceous flood basalts of the Rajmahal Traps in eastern India, the Kerguelen Plateau, and the adjacent regions of the southern Indian Ocean are widely considered to have erupted as a result of lithospheric interaction of the Kerguelen plume during the separation of India and Australia-Antarctica and the fragmentation of Gondwana at 165–133 Ma (Baksi et al., 1987; Storey et al., 1992; Kent et al., 1997, 2002; Coffin et al., 2002; Ghose and Kent, 2003). The lower parts of the Rajmahal succession contain inter-trappean layers of clastic sedimentary and volcaniclastic rocks, pockets and lenses of bentonite, and thin black shale/mudstone and oolitic beds (Roy Gupta, 1931; Deshmukh, 1964; Ghose et al., 1996). The inter-trappean sedimentary beds are rich in terrestrial plant fossils (Sengupta, 1988) that indicate a humid, sub-tropical climate. Similar fossil flora and fauna in sediments associated with the central Kerguelen Plateau basalts indicate terrestrial and shallow marine depositional environments (Mohr et al., 2002).

The aim of this paper is to describe the lithostratigraphy of lavas and inter-trappean volcaniclastic and sedimentary rocks, petrography of volcaniclastic rocks, associated lavas and oolitic sediments, and the mineral chemistry of enstatite-bearing basalts and andesites in order to address their origin and characterize the eruptive conditions during the early phase of Rajmahal volcanism.

2. Geological background

The Rajmahal Volcanic Province (RVP) is a ~4300 km^2, N–S elongate belt in eastern India at 24°00′–25°15′N and 87°20′–87°50′E on the northeastern continental margin of the Proterozoic Chotanagpur Gneissic Complex (CGC, Ghose, 1983; Chatterjee and Ghose, 2011). The CGC forms the basement of the Gondwana Supergroup, the uppermost part of which contains the Rajmahal flood basalts (Fig. 1). The CGC strikes E–W (Satpura orogenic trend) except in the northeast, where it bends northeastwards to become parallel to the Eastern Ghats orogenic belt (Ghose and Mukherjee, 2000). The eastern margin of the CGC is characterized by north-trending, east-dipping asymmetric folds that formed during high-grade metamorphism and deformation along the mid-Neoproterozoic Eastern Indian Tectonic Zone, a major linear orogen that extends from eastern India through the Kerguelen Plateau to East Antarctica (Chatterjee et al., 2010; Chatterjee and Nicolaysen, 2012). The Rajmahal eruptive centers are aligned north-south along the eastern and western margins of the RVP that are bounded by two major N–S faults, and there is a southward broadening gravity high over the eastern edge of the CGC near the RVP boundary (Mukhopadhyay et al., 1986; Singh et al., 2004) (Fig. 1). Thus, it is likely that the Rajmahal eruptions were guided by a major, pre-existing mid-Neoproterozoic lineament that may have been reactivated in the mid-Cretaceous. This is supported by multichannel reflection data that suggest emplacement of the Rajmahal Traps along a north-south pseudofault formed by the activity of the Kerguelen mantle plume (Desa et al., 2013). The structural control provided by the N–S pseudofault is supported by the elastic thickness (T_e) structure of the lithosphere in the region (Ratheesh-Kumar et al., 2014).

The Gondwana Supergroup consists of conglomerates, sandstones and shales of the lower Permian Talchir and Barakar (coal-bearing) formations, the upper Triassic/lower Jurassic Dubrajpur Formation, and the lower Cretaceous Rajmahal Formation with its flood basalts and inter-trappean beds containing fossil plants (Sengupta, 1988) (Fig. 1). Pebbly ferruginous sandstones and conglomerates of the Upper Dubrajpur Formation show the effects of induration and baking due to overlying lava flows. Seismic data indicate that the Rajmahal flows form a gentle southward-dipping homocline (Mukhopadhyay et al., 1986). The stratigraphic thickness of the basaltic succession is ~600 m, and the total thickness of the inter-trappean sedimentary beds is <35 m (Pascoe, 1975). The volcanic rocks are dominated by tholeiitic basalts and basaltic andesites with minor trachyandesites, andesites, dacites and rhyolites. Fifteen flows have been distinguished in surface outcrops; the thickness of individual flows is <1–85 m for basalt, 8–21 m for andesite, 12–17 m for dacite, and ~10–40 m for rhyolite (pitchstone) (Raja Rao and Purushottam, 1963; Sarbadhikari, 1968; Ghose et al., 1996). Inter-trappean beds of shale, black shale, mudstone, siltstone, cross-bedded sandstone (Fig. S-1A), and occasional coal seams are associated with bentonite lenses and volcaniclastic rocks. The presence of a "cone-in-crater type" vent in northwestern RVP (Ball, 1877), accretionary bombs in tuffaceous shales at the north-eastern margin, and welded tuffs and tuff breccia with spindle-shaped and flattened bombs in north-central RVP (Ghose et al., 1996) indicates that the pyroclasts were ejected violently through several N–S eruptive centers (Fig. 1).

The Rajmahal basalts extend eastward under Cenozoic sediments of the Bengal Basin and re-emerge at the southern edge of the Shillong plateau where they are known as the Sylhet Traps (Sengupta, 1966; Talukdar and Murthy, 1970; Baksi et al., 1987; Ghatak and Basu, 2011). The total area covered by the Rajmahal-Sylhet basalts is ~250,000 km^2 (Baksi, 1995). The basalts have ^{40}Ar-^{39}Ar ages of 118–115 Ma (Baksi, 1995; Kent et al., 2002; Ray et al., 2005), consistent with the chron C34n normal magnetic polarity of most Rajmahal lavas (Clegg et al., 1958; McDougall and McElhinny, 1970; Klootwijk, 1971). However, some basal lavas in the western RVP show reverse polarity (Klootwijk, 1971; Poornachandra Rao et al., 1996; Sherwood and Basu Mallik, 1996), and palynological data from boreholes in southern RVP indicate that volcanism may have begun as early as ~145–130 Ma (Vijaya and Bhattacharji, 2002). Remnant magnetic data indicate that the Rajmahal basalts erupted in mid-southern paleolatitudes (Clegg et al., 1958; Klootwijk, 1971; Poornachandra Rao et al., 1996) perhaps as a result of activity of the Kerguelen plume that formed a LIP comprising basalts of Rajmahal-Sylhet and the Kerguelen Plateau (Baksi et al., 1987; Storey et al., 1992; Kent et al., 1997, 2002; Coffin et al., 2002; Ghatak and Basu, 2013). The N–S oriented, E-dipping step-faults in the basement of the RVP and the adjoining Bengal Basin to the east have been attributed to the pre-Rajmahal break-up of Gondwana (Sengupta, 1966; Mukhopadhyay et al., 1986; Biswas, 1996).

3. Lithology and lithostratigraphy

All available detailed lithological sections from different parts of the RVP are summarized in Fig. 2. Here we describe the occurrence of volcaniclastic rocks, grey shales, black mudstone and oolitic sediments in the field, and new sections based on outcrops and a borehole drilled by the Geological Survey of India (Fig. 1).

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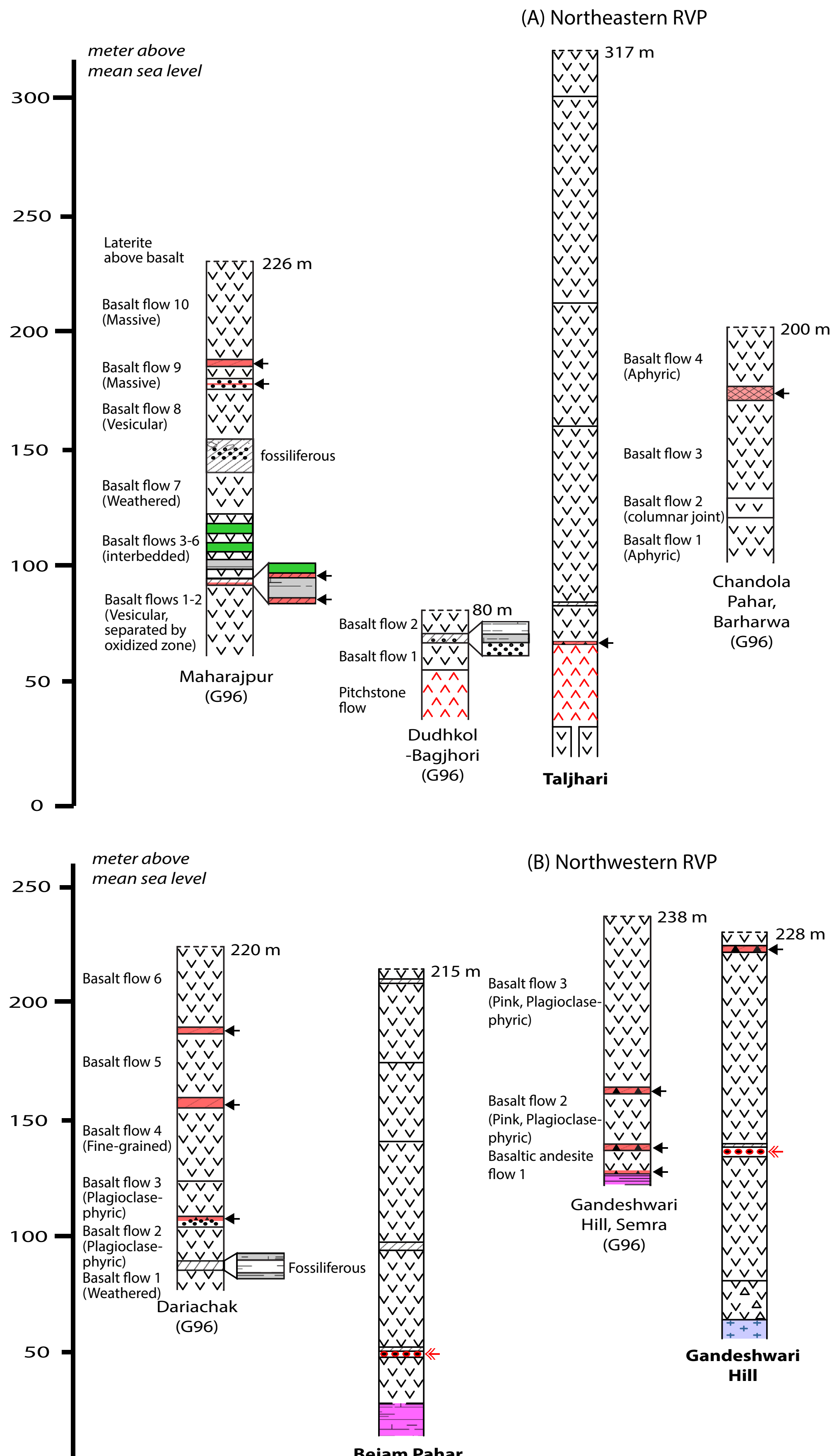
(A) Northeastern RVP
meter above
mean sea level
300
250
200
150
100
50
0
Laterite
above basalt
226 m
Basalt flow 10
(Massive)
Basalt flow 9
(Massive)
Basalt flow 8
(Vesicular)
fossiliferous
Basalt flow 7
(Weathered)
Basalt flows 3-6
(interbedded)
Basalt flows 1-2
(Vesicular,
separated by
oxidized zone)
Maharajpur
(G96)
80 m
Basalt flow 2
Basalt flow 1
Pitchstone
flow
Dudhkol
-Bagjhori
(G96)
317 m
Taljhari
200 m
Basalt flow 4
(Aphyric)
Basalt flow 3
Basalt flow 2
(columnar joint)
Basalt flow 1
(Aphyric)
Chandola
Pahar,
Barharwa
(G96)
(B) Northwestern RVP
meter above
mean sea level
250
200
150
100
50
0
220 m
Basalt flow 6
Basalt flow 5
Basalt flow 4
(Fine-grained)
Basalt flow 3
(Plagioclase-
phyric)
Basalt flow 2
(Plagioclase-
phyric)
Basalt flow 1
(Weathered)
Fossiliferous
Dariachak
(G96)
215 m
Bejam Pahar
238 m
Basalt flow 3
(Pink, Plagioclase-
phyric)
Basalt flow 2
(Pink, Plagioclase-
phyric)
Basaltic andesite
flow 1
Gandeshwari
Hill, Semra
(G96)
228 m
Gandeshwari
Hill

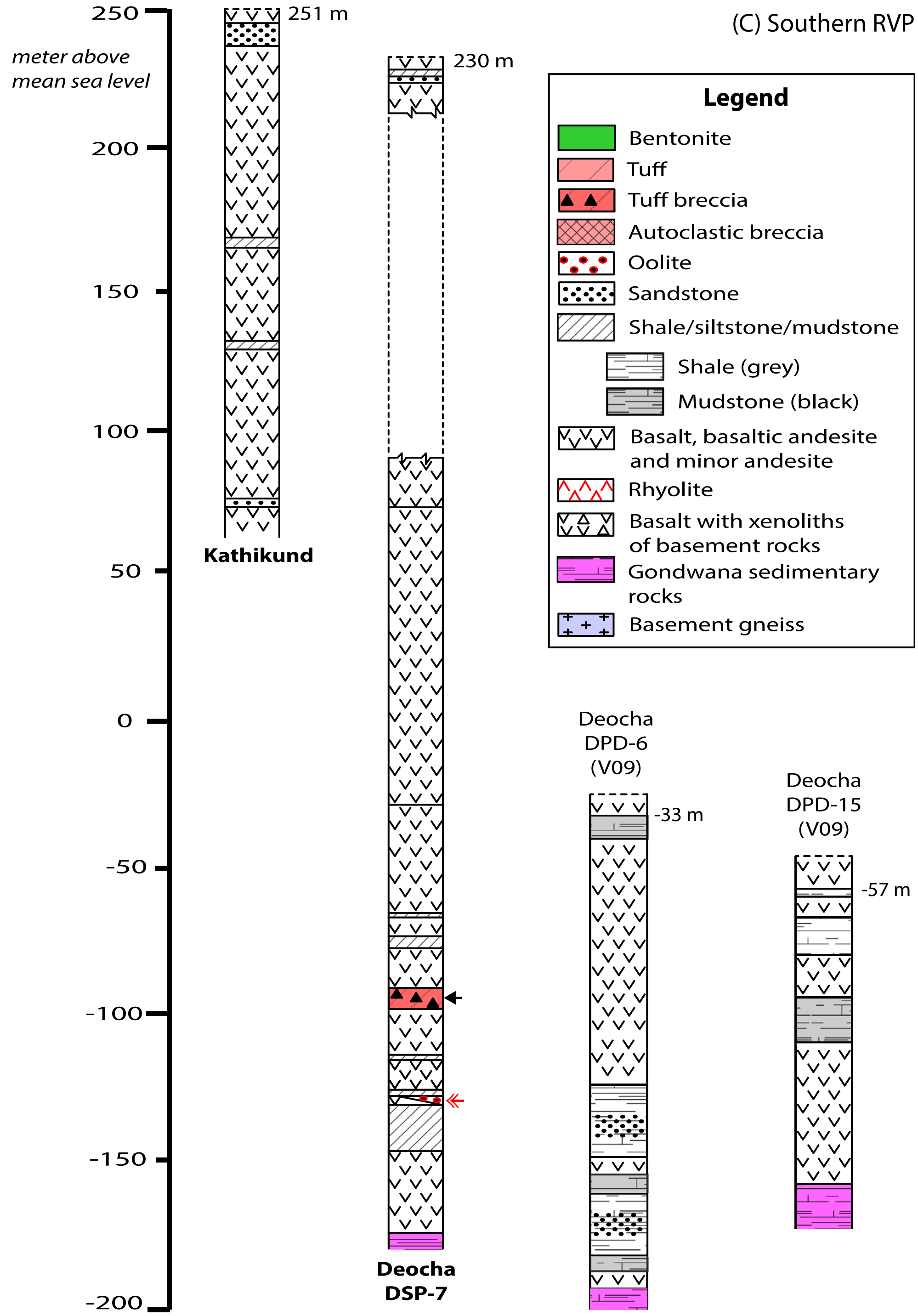

Figure 2. (*continued*).

3.1. Eastern margin

The Taljhari section is composed predominantly of porphyritic basalts except for a ~40 m-thick layer of pitchstone near the base at 30–70 m elevation (Fig. 2A). The pitchstone layer is fed by a feeder dike that intrudes through the underlying basalt, and it constitutes a flow that extends north-south for ~10 km with a maximum width of ~5 km (Fig. 1). There was probably a hiatus

Figure 2. Lithological sections of the Rajmahal volcanic succession at locations shown in Fig. 1. The elevations or depths below mean sea level of the different stratigraphic units are shown on the left. The occurrences of volcaniclastic rocks and oolite are marked by black and red arrows, respectively. (A, B) Based on field observations in the northeastern and northwestern margins of the RVP. Also shown are sections summarized from Ghose et al. (1996) (G96). (C) Based on drill-core data from borehole DSP-7 and field data from the southern tip of the RVP. The borehole sections DPD-6 and DPD-15 are summarized from Vijaya (2009) (V09). Locations: Maharajpur: 25°13′44″N, 87°43′38″E; Taljhari: 25°06′31″N, 87°43′24″E; Dudhkol-Bagjhori: 25°06′04″N, 87°44′01″E; Chandola Pahar: 24°53′41″N, 87°44′43″E; Dariachak: 25°07′36″N, 87°22′02″E; Bejam Pahar: 25°06′51″N, 87°21′52″E; Gandeshwari Hill (Semra): 25°01′33″N, 87°20′32″E; Gandeshwari Hill: 25°01′19″N, 87°20′35″E; Kathikund: 24°23′08″N, 87°25′25″E; Deocha: 24°03′51″N, 87°35′58″E.

between the eruptions of the lower basalt and the pitchstone. Five younger basaltic flows overlie the pitchstone flow. A thin inter-trappean layer of shale rich in fossil plants and ferruginous sandstone separates the two lower basaltic flows above the pitchstone at an elevation of ∼80 m. A thicker (∼5 m) inter-trappean layer of grey shale, black mudstone and sandstone occurs at an elevation of ∼70 m between the two basaltic flows above pitchstone at Dudhkol-Bagjhori. The Maharajpur section from the northeastern corner of the RVP also contains significant amounts of black mudstone and fossiliferous sandstone at ∼90, ∼100, and 140–155 m elevations (Ghose et al., 1996). The sedimentary layers are commonly interlayered with tuff. This section is also characterized by the presence of bentonite layers at ∼90, 110, and ∼120 m elevations.

About 1 km north of Taljhari railway station there is a 1 m-thick bed of coarse-grained tuff and tuff breccia between the pitchstone and the overlying basalt. The coarse-grained tuff and the tuff breccia contain 2–18 cm-sized bombs similar to those near Berhait in the north-central sector (see below). A thin oolitic layer is present within a bed of sandstone at Dudhkol, ∼2 km north of Taljhari railway station.

Two ∼50 m-thick, fine-grained lava flows of enstatite-bearing basalt and enstatite-andesite are separated by inter-trappean sedimentary beds at Tinpahar, south of Taljhari. The lower basaltic flow contains palagonite and amygdules filled with quartz and calcite near the top. Drilling at Tinpahar encountered the Dubrajpur Formation at 91 m below the surface (borehole RJR-2, Tripathi, 2008), or ∼50 m below m.s.l. estimated from the general surface elevation of ∼40 m of the Tinpahar area. This borehole also shows a ∼30 m thick inter-trappean layer ∼20 m above the contact with the Dubrajpur Formation (Tripathi, 2008).

Basaltic flows with no discernable inter-trappean beds occur at Chandola Pahar, south of Tinpahar. The second flow from the top is composed of trachyandesite capped by autoclastic breccia with clinker-like fragments of vesicular and scoriaceous trachyandesite embedded in fine-grained trachybasalt (Figs. 2A and 3B). Felsic tuff with pumice probably comes from a central vent or crater that is no longer preserved, but a satellite vent in a nearby quarry is associated with fine-grained basalt containing glassy amygdules and calcite (Fig. S-2A). Farther south along the eastern margin of RVP at Amsorhi Pahar (between Govindpur and Pakur), a welded ash flow tuff (ignimbrite) overlies basalt.

3.2. North-central sector

A ∼4 m-thick flow of welded tuff extends upstream from Berhait over a distance of ∼10 km along the Gumani River bed (Fig. S-1C). The welded tuff is associated with a narrow, N–S oriented ∼20 km long highly viscous pitchstone flow (Fig. 1), which is at the same stratigraphic level as the Taljhari pitchstone in northeastern RVP. Nearby, a tuff breccia contains coarse, 0.5–42.0 cm-sized, spindle-shaped bombs (Fig. 3A, Fig. S-1D).

3.3. Northwestern margin

In the Bejam Pahar section, the base of the volcanic succession is in contact with underlying Gondwana sedimentary rocks (Fig. 2B). Thin layers of inter-lava shale/siltstone grading into sandstone with ripple marks occur at ∼50, ∼90 and ∼210 m elevations. Between the two lowermost basaltic flows, ∼20 m above the volcanic base, a thin layer of siltstone occurs above a <1 m-thick oolitic bed. In the neighboring Dariachak section (Ghose et al., 1996), a ∼5 m thick layer of grey shale and black mudstone occurs at an elevation of ∼85 m, and tuff interlayered with sandstone occurs at elevations of ∼110, ∼160 and ∼185 m. About 15 km northeast of Dariachak, drill cores from two boreholes show an abundance of inter-trappean material including a ∼100 m section in the lower ∼250 m of the lava sequence (Tripathi, 2008).

The Gandeshwari Hill complex consists of four conical hills of pinkish altered basalt and basaltic andesite arranged in a northward-opening semi-circle (Ball, 1877). This study shows crystalline basement rocks below an elevation of ∼60 m overlain by plagioclase-phyric basalt with xenoliths of gneiss (Fig. 2B). A thin oolite (<1 m thick) associated with inter-trappean shale/siltstone occurs ∼75 m above the volcanic base. Another thin layer (∼1.5 m) of tuff breccia is sandwiched between basaltic flows at an elevation of ∼220 m. It is noteworthy that the pyroclastic, sedimentary and oolite layers occur within the lower ∼240 m of the lava sequence in all the sections (this study, and Tripathi, 2008) from the northwestern margin of the RVP.

3.4. Southern sector

In the Kathikund section on the southwestern edge of the RVP, thin shale-siltstone and sandstone beds occur between basaltic flows at ∼75, ∼130, ∼165 and 235–245 m elevations (Fig. 2C). Clasts of conglomerate and gritty sandstone derived from the Dubrajpur Formation underlying the volcanic sequence are present in the lowermost lava flow. The upper inter-trappean sedimentary layer is also encountered at an elevation of ∼225 m at the southern tip of the Rajmahal outcrop near Deocha.

Drill cores from a borehole in Deocha, ∼10 km south of the southern limit of the Rajmahal outcrop (Fig. 1), are dominated by at least six major basalt flows below a thin alluvial cover. A gritty Dubrajpur sandstone is encountered below the volcanic rocks at a

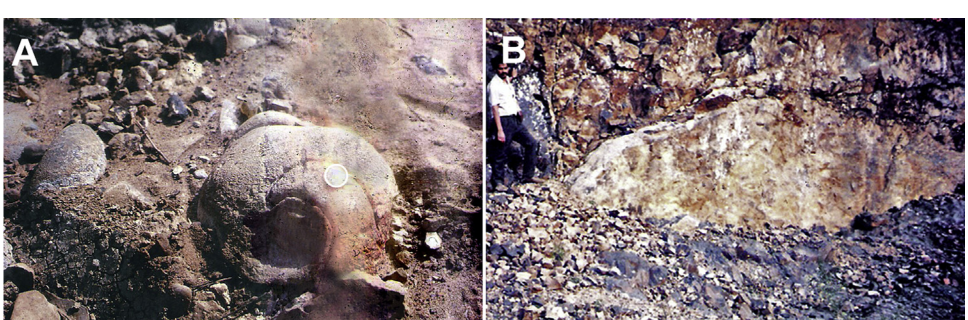

Figure 3. Field photographs of the Rajmahal volcanic outcrop. (A) Tuff breccia with bombs in the Gumani River, Berhait, north-central sector (24°54′03″N, 87°37′38″E); the largest bomb is ∼42 cm across (white circle encloses a coin). (B) Autoclastic breccia with a large lensoid fragment of altered reddish trachyandesite surrounded by smaller fragments mixed with soil (bluish tinge) at Chandola Pahar, northeastern margin (24°53′41″N, 87°44′43″E) traversed by felsic veins; the massive looking rock in the background is part of a lava flow.

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depth of ~175 m below mean sea level (m.s.l., Fig. 2C), as in neighboring boreholes (Vijaya, 2009). The lower ~100 m of the ~400 m-thick section contains a significant amount (~25 vol.%) of inter-trappean layers, tuff and oolite. A ~20 m-thick bed of inter-trappean shale/siltstone occurs at a depth of ~130–150 m below m.s.l., and there are similar thinner layers at ~125, ~115, ~75 and ~65 m depths below m.s.l.. A prominent ~10 m-thick tuff is sandwiched between two basaltic flows at ~90–100 m depth below m.s.l.. A thin (<1 m) bed of oolite pinches out within basalt below a thin sandstone bed (~50 m above the volcanic base). Irregular contacts formed by intermixing of vesicular lava and inter-trappean shale (peperitic?) occur in the lower parts of the section (Aniruddha Basu, personal communication, 1997). Other drill core samples from two different boreholes near Deocha also dominantly consist of grey shales, black mudstones and sandstones with the thickness of the inter-trappean layers varying between ~5 m and ~40 m (Vijaya, 2009). Lithologs from one borehole in the central RVP and three boreholes from the southern RVP also show abundant intertrappean material in the lower ~60 m of the Rajmahal sequence (Tripathi, 2008). Considering all the sections from the southern RVP, the sedimentary, pyroclastic and oolite layers occur within the lower ~240 m of the volcanic succession.

4. Geochemistry of andesite and rhyolite

Considerable high-quality geochemical data have been published on the Rajmahal volcanic rocks (Storey et al., 1992; Kent et al., 1997; Ghose and Kent, 2003), and thus we present only a few previously unpublished but relevant bulk analyses of felsic and intermediate rocks from the eastern margin of the RVP (Table 1). The key points that we wish to emphasize are: the Rajmahal andesites follow the trend of the basalts and basaltic andesites in a SiO_2 versus total alkali diagram (Fig. 4A), and their $(^{87}Sr/^{86}Sr)_i$ isotopic ratios (Fig. 4B) are similar to Group II Rajmahal basalts (Storey et al., 1992) that have been contaminated with continental crust. They show negative Nb-Ta anomalies and, except for andesite sample 88/34, large-ion-lithophile (LILE) and light rare-earth (LREE) element enrichments (Fig. 4C).

The Rajmahal rhyolites/dacites are separated from the andesites by a silica gap between >68 wt.% and <60 wt.% (Fig. 4A), and they show LILE and LREE enrichments and negative Nb-Ta anomalies (Fig. 4D).

5. Petrography and mineralogy

We place emphasis here on texture and mineralogy, because these are diagnostic of key environmental conditions in the eruption history. Below is a description of certain Rajmahal basalts, andesites and rhyolites that are directly relevant to the origin of the Rajmahal volcaniclastics rocks. This is followed by a detailed description of the volcaniclastic rocks and oolite.

5.1. Enstatite-bearing basalt, enstatite-andesite and rhyolite

The lower Rajmahal basalts are dominantly porphyritic, whereas the upper basalts are fine-grained and aphyric. The porphyritic basalts show intergranular, sub-ophitic, glomeroporphyritic and trachytic textures, and contain phenocrysts of plagioclase (An_{73-53}), minor augite ($En_{46-48}Wo_{35-39}Fs_{14-19}$) and Fe-Ti oxides in a fine-grained groundmass of plagioclase, augite, pigeonite and devitrified glass (Poornachandra Rao et al., 1996; Ghose and Kent, 2003). They also contain rare altered olivine (Ball, 1877; Kent et al., 1996) and mantle-derived websterite xenoliths (Fig. S-3A). By comparison, the enstatite-bearing basalts from Tinpahar (northeastern margin) have intergranular to intersertal textures, and they contain

Table 1
Chemical composition of orthopyroxene and whole rock from the Tinpahar–Taljhari area, northeastern margin of RVP.

Sample	Opx		Bulk rock					
	EB89-63[a,†]	RB37[b,‡]	EB89-63[a]	DPD-7[a]	S/64[a]	S/129[a]	S/111[a]	S/130[c]
in wt.%								
SiO_2	55.68	53.87	57.41	56.21	57.70	58.17	58.23	64.87
TiO_2	0.15	0.31	1.01	1.01	1.01	1.31	1.21	1.10
Al_2O_3	1.55	3.39	16.17	13.27	12.57	12.57	13.97	14.67
Cr_2O_3	0.43	0.06						
Fe_2O_3			0.02	2.26	2.85	1.13	8.30	4.95
FeO	9.07	11.01	6.45	10.26	7.38	10.08		
MnO	0.26	0.34	0.07	0.20	0.20	0.18	0.12	0.08
MgO	31.80	29.06	5.25	4.64	6.22	5.25	7.05	1.11
CaO	0.98	1.16	7.72	5.08	6.49	5.34	3.96	1.71
Na_2O	0.08	0.07	4.20	3.22	3.05	3.37	3.86	3.71
K_2O	0.03	0.03	0.36	0.69	0.36	0.26	0.44	3.16
P_2O_5				0.05	0.04	0.04	0.05	0.04
LOI				2.93	1.68	2.18	1.08	2.60
Total	100.03	99.30	98.66	99.82	99.55	99.88	98.27	98.00
Cation sum	4.010	4.004						
$Mg^{\#}$	86.2	82.5	59.1	40.2	52.7	45.8	62.7	30.8
En	84.3	80.1						
Fs	13.9	17.6						
Wo	1.9	2.3						

Orthopyroxene from Punjabi Khadan, SW of Tinpahar, analyzed by EPMA at PPOD, GSI, Bangalore; Bulk data sources: Unpublished and A. Basu, pers. comm.; [a]andesite, [b]basalt, [c]dacite, $Mg^{\#} = 100 \times Mg/(Mg + Fe^T)$ where Fe^T is total Fe, and Mg and Fe are number of atoms of the elements, En: enstatite, Fs: ferrosilite, Wo: wollastonite, [†]non-pleochroic, [‡]pleochroic.

phenocrysts of green-to-pink pleochroic ($En_{80}Fs_{18}Wo_2$, Table 1) and non-pleochroic orthopyroxene, and minor clinopyroxene in a fine-grained groundmass of plagioclase, titanomagnetite and glass (Fig. 5A, Fig. S-3B,C). Importantly, siltstone xenoliths with melted quartzo-feldspathic rims and quartz xenocrysts with reacted margins are common in the enstatite-bearing basalts (Fig. 5B,C). The Tinpahar enstatite-andesites (Fig. S-3D-F) have a fine-grained vitrophyric texture, and they contain phenocrysts of non-pleochroic multiple-twinned orthopyroxene ($En_{84}Fs_{14}Wo_2$, Table 1) in a groundmass of glass (~70 vol.%) with minor (<5 vol.%) twinned plagioclase, low-Ca amphibole, serpentine and opaques.

The rhyolites (pitchstones) from Taljhari, north of Tinpahar have fine-grained microporphyritic, ophitic and poikilitic textures. They contain phenocrysts of feldspar, minor pleochroic orthopyroxene, clinopyroxene and tile-structured tridymite (Fig. 5D) in a groundmass of glass showing perlitic cracks (≤66 vol.% glass, Deshmukh, 1964). The groundmass contains minor cristobalite (Das Gupta, 1996), and accessory magnetite and pyrite. The phenocrysts decrease in abundance upwards within the flow.

5.2. Volcaniclastic rocks

Most (~90 vol.%) of the Rajmahal volcaniclastic rocks are recognized as pyroclastic rocks on the basis of grain size, and their mechanism of primary transport and deposition (White and Houghton, 2006). The rest are autoclastic rocks (Fig. 3B) and peperites.

5.2.1. Felsic pyroclastic rocks (north-central sector and northeastern margin)

The *tuff breccia* from the Gumani River, Berhait (north-central, Fig. 3A, Fig. S-1D), and from the bed between pitchstone and basalt near the base of the Taljhari (northeast) section (Fig. 2A) contain pyroclasts of various shapes and sizes embedded in ash. The large pyroclasts are represented by bombs composed of a concentric outer shell of fine-grained cryptocrystalline quartz, an inner layer of well-developed transparent quartz, and a core of amethyst. The Taljhari-Dudhkol *coarse-grained tuff* consists of angular, conduit-derived magmatic clasts (Fig. 6A, Fig. S-2B), poorly sorted juvenile

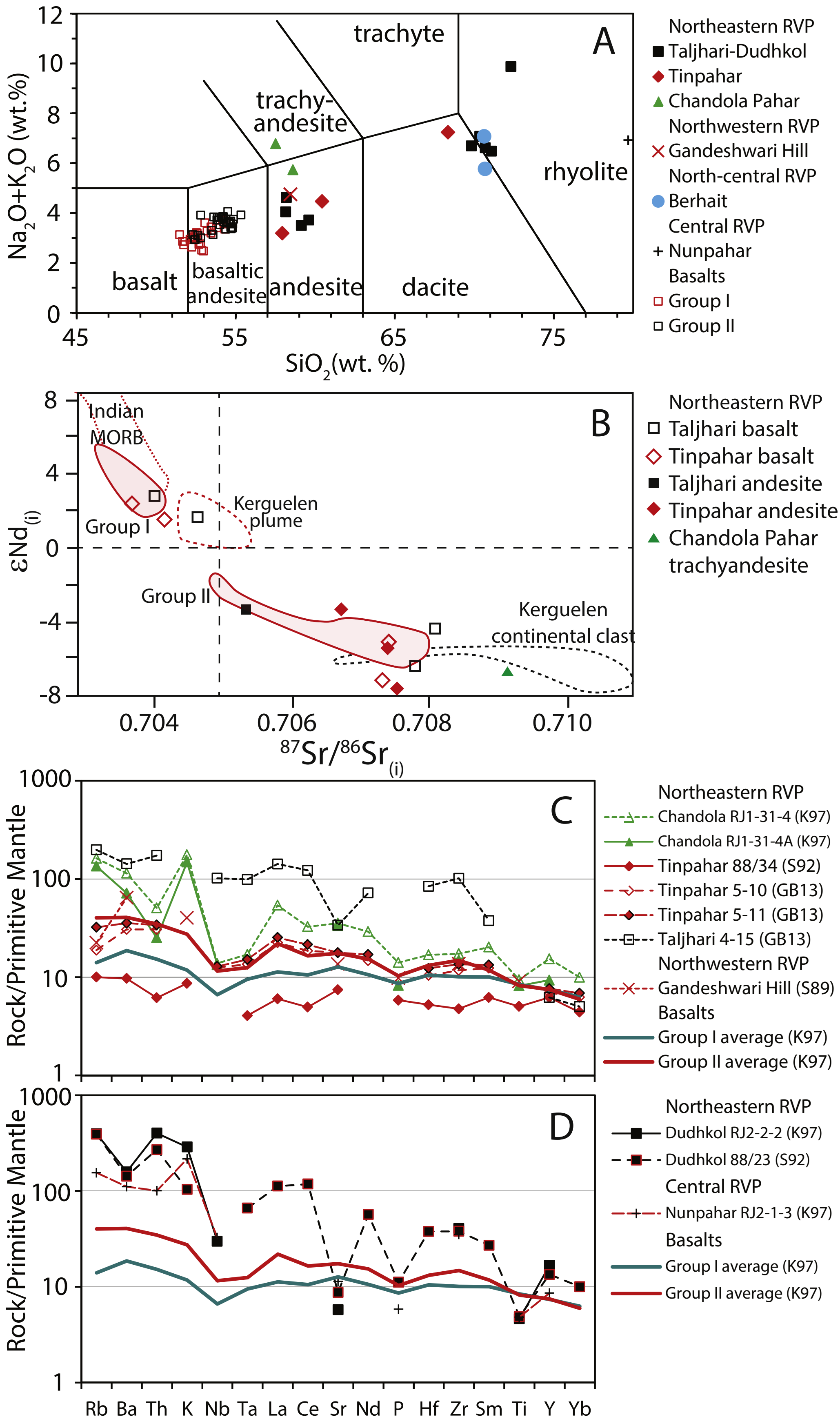

Figure 4. Bulk chemical and isotopic compositions of Rajmahal intermediate and felsic rocks compared with the less-contaminated (Group I) and contaminated (Group II) Rajmahal basalts and basaltic andesites. (A) Total alkali versus SiO_2 based on Le Bas et al. (1986) (data from K97, S92, D64, RP63, GK03, S89, S68 and Table 1); (B) Nd-Sr isotope systematics (data from K97, GB13, S92 and I02); (C and D) Primitive mantle-normalized (McDonough and Sun, 1995) incompatible element patterns of (C) andesites and (D) rhyolites. The abbreviations are D64: Deshmukh (1964); GB13: Ghatak and Basu (2013); GK03: Ghose and Kent (2003); I02: Ingle et al. (2002); K97: Kent et al. (1997); RP63: Raja Rao and Purushottam (1963); S68: Sarbadhikari (1968); S89: Sarkar et al. (1989); S92: Storey et al. (1992).

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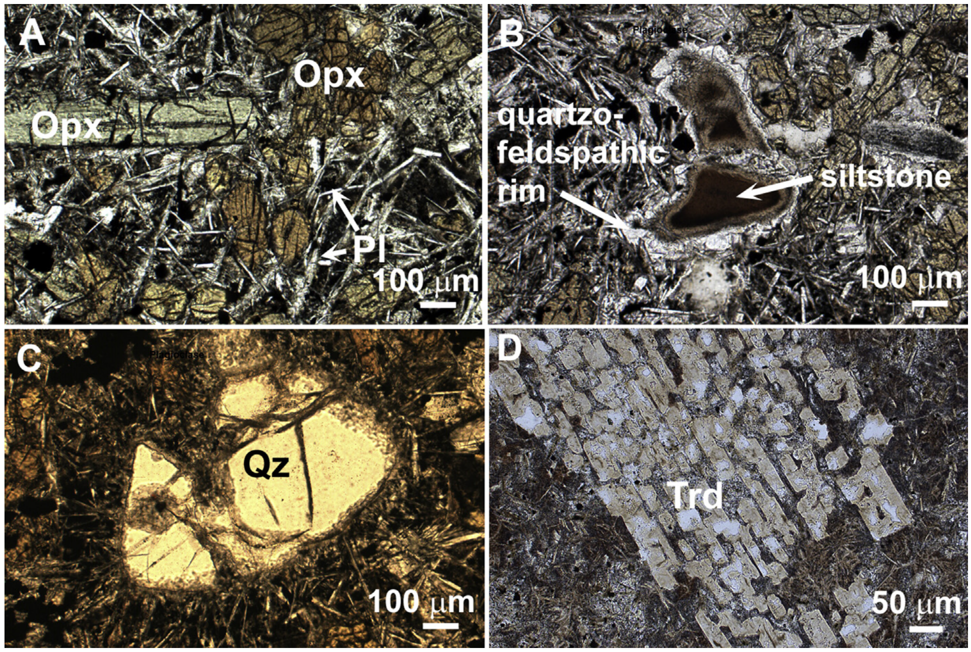

Figure 5. Photomicrographs of volcanic rocks from the northeastern margin: (A–C) Tinpahar (24°59′30″N, 87°44′24″E) enstatite-bearing basalt rb89/37-3, and (D) Taljhari-Dudhkol (25°06′04″N, 87°44′01″E) rhyolite eb89-100-6-4. (A) Pleochroic orthopyroxene (Opx) phenocrysts in an intergranular groundmass with acicular ophitic plagioclase (Pl) and opaque titanomagnetite. (B) Siltstone xenolith with a melted quartzo-feldspathic rim in enstatite-bearing basalt. (C) Quartz (Qz) xenocryst with reacted margin and glass-filled fractures in basalt with a chilled margin. (D) Tridymite (Trd) phenocryst with tile structure in a glassy groundmass.

quartz, feldspar and glass, and composite blocks of sediment (Fig. 6B) in a fine-grained matrix.

The *welded tuff* (ignimbrite) from Amsorhi Pahar, Govindpur-Pakur (eastern margin), consists of viscous layers containing devitrified pumice shards, and bands of frayed, flame-like terminations of *fiamme* (Fig. 6C). Spherules of devitrified glass are present in some samples (Fig. 6D) indicating high temperature of formation.

5.2.2. *Mafic pyroclastic rocks (northwestern margin)*

Fine-grained tuffs from the Gandeshwari Hill sections (Fig. 2A) contain angular vesicle-poor sideromelane shards, quenched glass with arcuate fractures, micro-lapilli of glass with devitrified margins, quenched juvenile clinopyroxene with acicular crystal habits (Fig. 7A–C), plagioclase, quartz, feldspar and glass, and recycled plagioclase with glass-filled fractures and clinopyroxene (Figs. S-4, S-5A). These tuffs show normal grading of grain-size, flattened

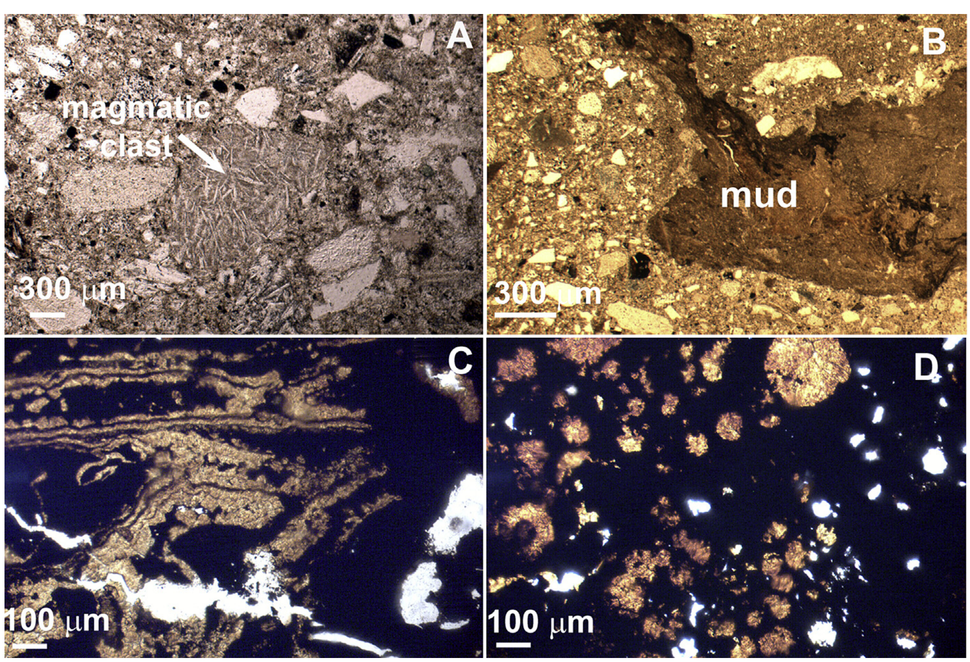

Figure 6. Photomicrographs of felsic pyroclastic rocks from the eastern margin: (A, B) coarse-grained tuff with lithic clasts from Taljhari, northeastern margin (25°05′36″N, 87°44′31″E), and (C, D) welded tuff (ignimbrite) rb-15-3 from Amsorhi Pahar, Govindpur, eastern margin (24°37′55″N, 87°50′40″E). (A) Conduit-derived magmatic clasts and angular pyroclasts of variable size (sample dud-tu-8). (B) Angular fragments of juvenile quartz, feldspar and glass, small lithic clasts of wall rock, and a composite block of sediment (mud) (sample dud-tu-12). (C) Layers and fiamme structures (black) aligned in the flow direction (white patches are vesicles). (D) Glass spherules and vesicles in a devitrified glassy matrix.

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pyroclasts perpendicular to the layers, density layering of minerals, and flow-related vesicle trails associated with the pyroclasts similar to convolute bedding (Fig. 7D,E, Fig. S-5B-E). Some welded *tuff breccia* from Gandeshwari Hill contain angular basaltic grains probably derived from a vent/crater wall, and resorbed plagioclase in a devitrified glassy matrix (Fig. 7F, Fig. S-5F).

5.2.3. Peperite

Peperite from Gandeshwari Hill consists of beds of lithified mixtures of volcanic and sedimentary clasts with some layers rich in pumice and lava fragments, and others rich in clasts of clastic sediment (Fig. 8A, Fig. S-6A,B). Similar peperites occur in the lower parts of the sections at Deocha (southern RVP, Section 3.4).

5.3. Oolite

The oolite from Dudhkol (eastern RVP) consists of <2 mm sized ooids cemented by fine- to medium-grained calcite, iron-rich material, and/or micro-organisms (Fig. 8B). The ooids have an onion-shell structure with well-developed concentric growth rings of calcium carbonate around a silicate or carbonate nucleus. Similar oolites occur at the northwestern margin and at Deocha.

6. Discussion

6.1. Petrogenesis of enstatite-andesite and rhyolite

The isotope and trace element data of the Rajmahal andesites (Fig. 4B,C) indicate that they are contaminated by upper continental crust. The absence of LILE and LREE enrichments in the Tinpahar enstatite-andesite 88/34 ($Mg^{\#} = 64.3$, Storey et al., 1992) may be attributed to its origin in depleted mantle at a spreading ridge followed by upper crustal contamination. Interaction between the Kerguelen plume and a spreading ridge near the Indian rifted margin was suggested by Kent et al. (2002).

Siltstone xenoliths with melted quartzo-feldspathic rims in enstatite-bearing basalts (Fig. 5E, cf. Tuttle and Bowen, 1958; Winkler and Ghose, 1973) provide definitive evidence of formation of the andesites by upper crustal contamination of basaltic magma. Andesitic liquids can be produced by mixing of a basaltic liquid with upper crustal material that changes the fractionating assemblage from olivine + plagioclase + clinopyroxene to an orthopyroxene-bearing assemblage through a crustal assimilation-fractional crystallization (AFC) process (Grove and Baker, 1984). Crystallization of ferro-enstatite at temperatures of <1080 °C due

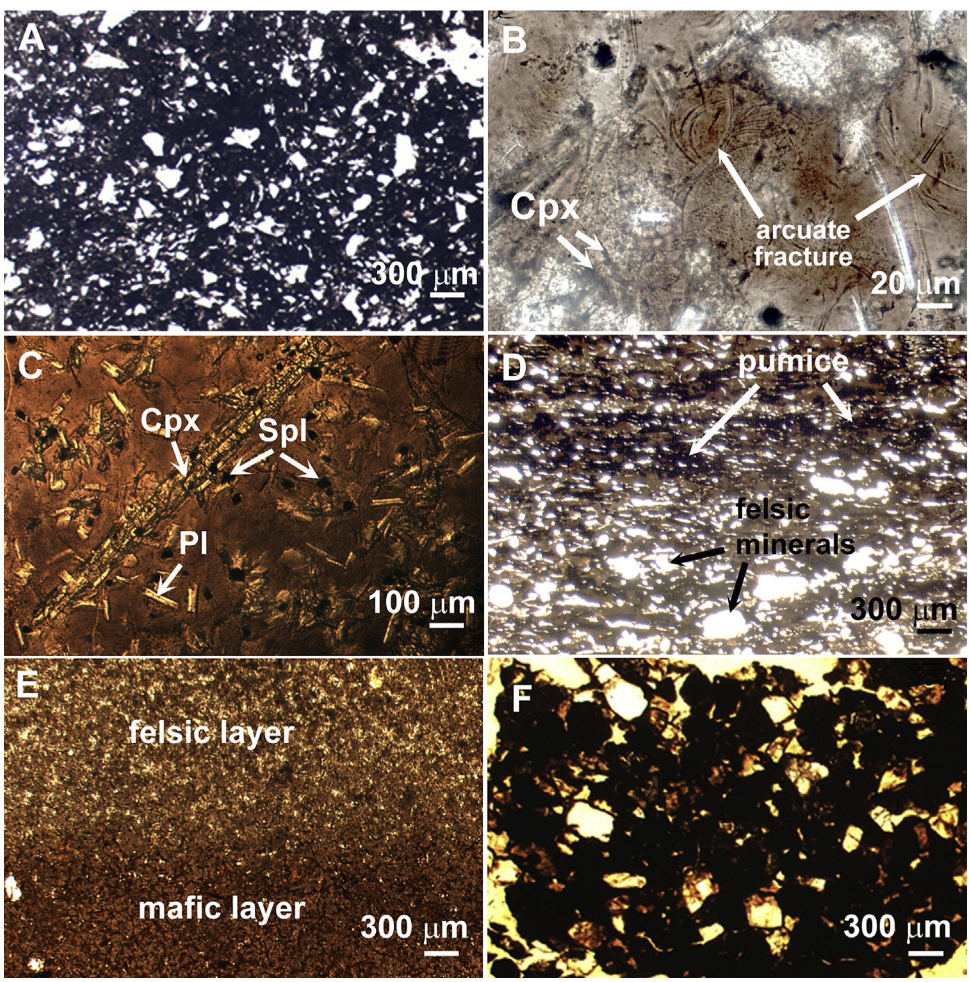

Figure 7. Photomicrographs of mafic pyroclastic rocks from Gandeshwari Hill, northwestern margin (25°01′33″N, 87°20′32″E). (A) Fine-grained tuff with angular, vesicle-poor sideromelane shards (sample gan-3-90-1). (B) Glass shards with arcuate fractures, subhedral clinopyroxene (Cpx) and needles fine-grained plagioclase (white) (sample tb-89/95-3). (C) Basaltic tuff showing quenched texture with long acicular clinopyroxene, plagioclase (Pl) laths and granular spinel (Spl) (sample eb-89-104-7). (D) Fine-grained tuff with flattened felsic mineral grains and pumice shards parallel to the bedding and normal grading with an upward decrease in grain-size (sample rb-28-1). (E) Density layering in fine-grained tuff with a lower mafic bottom grading into an upper felsic top (sample eb-89-104-1). (F) Angular juvenile crystals and basaltic shards in welded tuff breccia with resorbed grains of pyroxene (brown) and plagioclase (light color) (sample eb-89-1).

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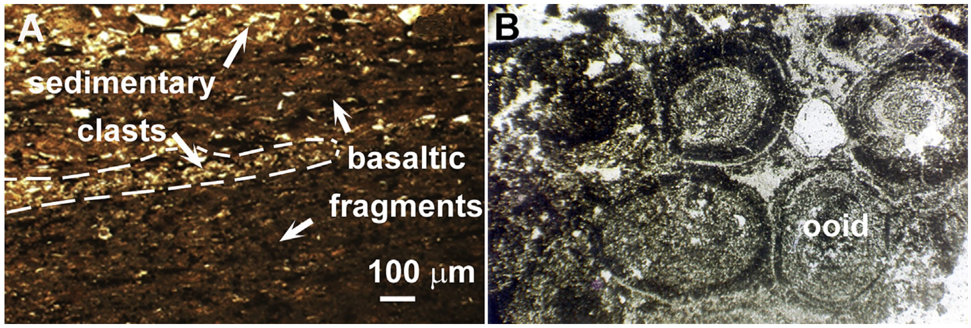

Figure 8. Photomicrographs of (A) peperite from Gandeshwari Hill, northwestern margin (25°01′33″N, 87°20′32″E), showing inter-fingering of layers (as demarcated by dashed line) of dark basaltic fragments and sedimentary clasts (sample (rb-28-4), and (B) oolite from Dudhkol, northeastern margin (25°06′04″N, 87°44′01″E) with ooids cemented by carbonate and with concentric growth layers of carbonate around a nucleus of sand or a shell fragment (×35 magnification).

to assimilation of shale by basaltic magma has been documented in the Deccan Traps (Chandrasekharam et al., 2000). Orthopyroxene-liquid thermobarometry (Equations 28a and 29a in Putirka, 2008) using the orthopyroxene and bulk rock compositions of the Tinpahar enstatite-andesite EB89-63 (Table 1) yields a temperature of 1147–1166 °C and an upper crustal pressure of 2.8–3.6 kb.

The trace element data of the rhyolites (Fig. 4D) are also consistent with an upper crustal origin. However, the rhyolites/dacites are separated from the andesites by a silica gap between <60 wt.% and >68 wt.% (Fig. 4A), indicating that there was no mixing between the basaltic magma and the upper crust. They probably originated through crustal anatexis with only heat supplied by the basaltic magma. Such an origin of rhyolite has been demonstrated in the Deccan (Chatterjee and Bhattacharji, 2001, 2004; Sheth et al., 2011). The >250 m-thickness of basalts overlying the ~40 m-thick rhyolite at Taljhari (Fig. 2B) indicates that the voluminous upper basalts were erupted only after the rhyolitic melts had been completely expelled from the plumbing system. A similar plumbing system was probably present ~30 km SSW of Taljhari at Berhait in north-central RVP, where there are extensive pitchstone flows (Fig. 1), and it is possible that the two systems were interconnected.

Ascending rhyolitic melts may intersect the quartz-tridymite phase boundary and crystallize feldspar + tridymite at a temperature of 890 °C by isothermal decompression to very shallow depths (0.16 kb, Blundy and Cashman, 2001). During this process, the rhyolitic melt may become water-saturated and form bubbles. The presence of amygdules and tile-structured tridymite in the Rajmahal pitchstone (Fig. 5A) indicates that it was probably generated by the above process. The temperature of the rhyolitic liquid was ≥867 °C, the quartz-tridymite transition temperature at atmospheric pressure (Tuttle and Bowen, 1958).

The formation of such a highly viscous felsic magma set the stage for explosive eruptions in the north-central sector and on the northeastern margin of the RVP, as discussed below.

6.2. *Environment and style of early eruptions*

Lithological sections from the different parts of the RVP show that the inter-trappean sedimentary, pyroclastic and oolite layers are confined to the lower ~240 m (i.e., approximately the lower one-third, Fig. 2) of the ~600 m-thick Rajmahal volcanic succession (Pascoe, 1975). Composition of these inter-trappean layers provides important clues to the environment and style of the early Rajmahal eruptions. These layers are composed of clastic sediments, grey and black shales/mudstones, oolite, pyroclastic rocks, bentonite, peperite (Figs. 2–8) and plant fossils (Sengupta, 1988). Altogether eight layers of shales/mudstones (four in surface outcrops and four subsurface) and three layers of oolite (two in surface outcrops and one subsurface) have been identified in the lithological sections. In addition, pockets and lenses of bentonite occur in much of the northeastern RVP (e.g., lower part of the Maharajpur section, Fig. 2A). The bentonite contains illite (Das Gupta, 1996) that indicates diagenesis under marine condition (Rankama and Sahama, 1964), and the presence of grey and black shale/mudstone and oolite points to deposition in the warm waters of a lagoon or similar coastal water body.

Felsic pyroclastic rocks are present between the pitchstone flows and the overlying basalts in the lower part of the Taljhari section (northeastern margin, Fig. 2A), and they are associated with the pitchstone flows near Berhait (north-central sector). These pyroclastic rocks comprised of tuff breccia with spindle-shaped pyroclasts (bombs) (Fig. 3A, Fig. S-1D) and coarse-grained tuffs with angular, conduit-derived magmatic fragments, poorly sorted juvenile quartz, feldspar and glass, and sedimentary blocks (Fig. 6A,B) indicate explosive eruptions of viscous rhyolitic magma from a deep plumbing system. The presence of fine- to medium-grained siliceous lapilli and bentonite derived from aqueous alteration of ash (cf. Christidis and Huff, 2009) over a large part of the northeastern RVP (Das Gupta, 1996) indicates that airborne pyroclasts traveled over long distances. The extensive presence of illite-bearing bentonite (e.g., Maharajpur, Fig. 2A) and oolite (e.g., Dudhkol, Fig. 8B) in the lower parts of the sections indicate that explosive felsic volcanism primarily occurred under subaqueous conditions in the northeastern RVP. However, the felsic eruptions also generated pyroclastic density currents that formed the welded tuffs with *fiamme* structures and glass spherules (Fig. 6C,D) perhaps in subaerial conditions.

The exclusively mafic pyroclastic rocks (fine-grained tuff) from Gandeshwari Hill contain angular vesicle-poor sideromelane shards (Fig. 7A) consistent with formation by rapid cooling and quenching by external water (Fisher and Schmincke, 1984, p. 76–77 and 97). The quenched textures (Fig. 7B,C) imply formation through thermal shock that likely occurred in a phreatomagmatic environment (Fisher and Schmincke, 1984, p. 236; cf. Kshirsagar et al., 2011, in the Deccan). The welded tuff breccia (Fig. 7F, Fig. S-5F) at Gandeshwari Hill possibly formed through base surges (Fisher and Schmincke, 1984). Peperite (Fig. 8A, Fig. S-8A) likely formed as a result of intrusion of mafic magma into wet unconsolidated sediments at a shallow depth (cf. Kshirsagar et al., 2011). Pink coloration of the Gandeshwari Hill basalts also likely resulted from extensive high temperature deuteric oxidation of titanomagnetite to titanohematite + pseudobrookite (Sherwood and Basu Mallik, 1996) in the presence of water. Shallow marine conditions are substantiated by the presence of black shales/mudstones in the lower part of the Dariachak section, and oolite in the lower parts of the Gandeshwari Hill and Bejam Pahar sections (Fig. 2A). Thus, the early Rajmahal mafic lavas on the northwestern margin of the RVP were erupted explosively in a predominantly subaqueous environment.

The early Rajmahal eruptions took place in an extensional tectonic setting accompanied by rifting, which likely facilitated recurring marine transgressions in the shallow coastal Rajmahal basin on account of eustatic sea-level fluctuations for a short duration. Sedimentological studies indicate episodic marine transgressions in a broadly fluvial environment throughout the period of Gondwana sedimentation (Mahadevan, 2002, p. 427) that likely continued during the early phase of Rajmahal volcanism. The inter-trappean sedimentary (especially grey and black shales/mudstones), pyroclastic and oolitic rocks in the lower one-third of the Rajmahal succession provide evidence for a subaqueous environment for eruption of the early Rajmahal lavas. In contrast, the upper two-thirds of the Rajmahal succession are devoid of inter-trappean sedimentary and volcaniclastic rocks. This can be attributed to effusive subaerial mafic eruptions in a relatively stable tectonic setting that formed the voluminous upper basaltic flows.

7. Conclusions

Interaction between basaltic magma and the upper continental crust generated the enstatite-andesites and rhyolites on the northeastern margin of the RVP. The presence of siltstone xenoliths with melted quartzo-feldspathic rims in enstatite-bearing basalts indicates that the enstatite-bearing basalts and enstatite-andesites originated by mixing of basaltic magma with the upper crust, resulting in the crystallization of orthopyroxene at upper crustal pressures ($\sim$3 kb) and temperatures of $\sim$1150 °C. On the other hand, the rhyolites formed by upper crustal anatexis with only heat supplied by the basaltic magma. The presence of tridymite in rhyolite may indicate temperatures of $\geq$867 °C of the felsic magma. The voluminous upper basaltic flows were erupted after the rhyolitic liquids were expelled from a possibly large interconnected plumbing system between the north-central sector and the northeastern margin of the RVP.

Primary volcaniclastic rocks along with inter-trappean sedimentary beds with grey and black shales/mudstones, and thin oolite layers make up an average of 25 vol.% of the lower one-third of the Rajmahal volcanic succession. In the north-central sector and the eastern margin of the RVP, viscous rhyolitic magma erupted violently to form coarse-grained tuffs with lithic clasts, and tuff breccia with bombs and lapilli, and it generated pyroclastic density currents that led to the emplacement of welded tuffs and ignimbrites of felsic composition. The extensive presence of illite-bearing bentonite, grey and black shale/mudstone and oolite over much of the northeastern RVP, and the sedimentological record of episodic marine transgressions in a coastal fluvial environment indicate shallow marine to subaerial eruptive conditions of the early Rajmahal lavas in the north-central and northeastern sectors. Furthermore, the presence of oolite and grey and black shale/mudstone in the lower parts of the Rajmahal succession (e.g., shale/mudstone between −33 m and −170 m at Deocha) indicate a predominantly shallow marine, continental shelf-type environment at the northwestern and southern margins of the RVP. The highly fragmented mafic pyroclastic rocks with quenched textures (hydroclastic rocks) on the northwestern margin of the RVP likely formed through explosive eruptions of mafic magma in a subaqueous environment.

The presence of grey and black shale/mudstone and oolite in the northeastern, northwestern and southern parts of the RVP probably indicates an extensive lagoonal or coastal marine environment throughout the RVP during the early eruptive phase. The occurrence of illite-bearing bentonite in the northeast, and mafic tuffs with peperite in the northwest in this context supports a shallow marine environment.

The voluminous younger basalts of the RVP were erupted by effusive subaerial volcanism. The variable geological conditions in space and time that prevailed in the area during Rajmahal volcanism were well summarized by Ball (1877), who stated " …. volcanic flows were taking place in some place, while clays and mud were deposited in others at the same time".

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.gsf.2016.06.007.

References

Baksi, A.K., 1995. Petrogenesis and timing of volcanism in the Rajmahal flood basalt province, Northern India. Chemical Geology 121, 73–90.
Baksi, A.K., Barman, T.R., Paul, D.K., Ferar, E., 1987. Widespread early Cretaceous flood basal volcanism in eastern India: geochemical data from the Rajmahal-Bengal-Sylhet traps. Chemical Geology 63, 133–141.
Ball, V., 1877. Geology of the Rajmahal Hills. Geological Survey of India Memoir 13, 155–248.
Bell, B.R., Emeleus, C.H., 1988. A review of silicic pyroclastic rocks of the British Tertiary Volcanic Province. In: Morton, A.C., Parson, L.M. (Eds.), Early Tertiary Volcanism and the Opening of the NE Atlantic, Geological Society, London, Special Publication 39, pp. 365–379.
Beane, J.E., Turner, C.A., Hooper, P.R., Subbarao, K.V., Walsh, J.N., 1986. Stratigraphy, composition and form of the Deccan Basalts, Western Ghats, India. Bulletin of Volcanology 48, 61–83.
Bellieni, G., Comin-Chiaramonti, P., Marques, L.S., Melfi, A.J., Nardy, A.J.R., Papatrechas, C., Piccirillo, E.M., Roisenberg, A., Stolfa, D., 1986. Petrogenetic aspects of acid and basaltic lavas from the Parana plateau (Brazil): geological, mineralogical, and petrochemical relationships. Journal of Petrology 27, 915–944.
Biswas, S.K., 1996. Mesozoic volcanism in the east coast basins of India. Indian Journal of Geology 68, 237–254.
Blundy, J., Cashman, K., 2001. Ascent-driven crystallization of dacitic magmas at Mount St Helens, 1980–1986. Contributions to Mineralogy and Petrology 140, 631–650.
Bond, D.P.G., Wignall, P.B., 2014. Large Igneous Provinces and Mass Extinctions: An Update. Geological Society of America, Special Papers 505, pp. 29–55.
Bryan, S.E., Riley, T.R., Jerram, D.A., Stephens, C.J., Leat, P.L., 2002. Silicic volcanism: an undervalued component of large igneous provinces and volcanic rifted margins. In: Menzies, M.A., Klemperer, S.L., Ebinger, C.J., Baker, J. (Eds.), Volcanic Rifted Margins, pp. 97–118.
Carlson, R.W., Hart, W.K., 1988. Flood basalt volcanism in the northwestern United States. In: Macdougall, J.D. (Ed.), Continental Flood Basalts. Kluwer, Dordrecht, Netherlands, pp. 35–61.
Chandrasekharam, D., Vaselli, O., Sheth, H.C., Keshav, S., 2000. Petrogenetic significance of ferro-enstatite orthopyroxene in basaltic dikes from the Tapi rift, Deccan flood basalt province, India. Earth and Planetary Science Letters 179, 469–476.
Chatterjee, N., Bhattacharji, S., 2001. Origin of the felsic dikes and basaltic dikes and flows in the Rajula-Palitana-Sihor area of the Deccan Traps, Saurashtra, India: a geochemical and geochronological study. International Geology Review 43, 1094–1116.

Chatterjee, N., Bhattacharji, S., 2004. A preliminary geochemical study of zircons and monazites from Deccan felsic dikes, Rajula, Gujarat, India: implications for crustal melting. In: Sheth, H.C., Pande, K. (Eds.), "Magmatism in India through Time", Proceedings of Indian Academy of Sciences, Earth and Planetary Sciences 113 (4), pp. 533–542.

Chatterjee, N., Ghose, N.C., 2011. Extensive Early Neoproterozoics high-grade metamorphism in north Chotanagpur Gneissic Complex of the Central Indian Tectonic Zone. Gondwana Research 20, 362–379.

Chatterjee, N., Nicolaysen, K., 2012. An intercontinental correlation of the mid-Neoproterozoic Eastern Indian Tectonic Zone: evidence from the gneissic clasts in Elan Bank conglomerate, Kerguelen Plateau. Contributions to Mineralogy and Petrology 163, 789–806.

Chatterjee, N., Banerjee, M., Bhattacharya, A., Maji, A.K., 2010. Monazite chronology, metamorphism–anatexis and tectonic relevance of the mid-Neoproterozoic Eastern Indian Tectonic Zone. Precambrian Research 179, 99–120.

Clegg, J.A., Radhakrishnamurthy, C., Sahasrabudhe, P.W., 1958. Remnant magnetism of the Rajmahal traps of northeastern India. Nature 181, 830–831.

Coffin, M.F., Pringle, M.S., Duncan, R.A., Gladczenko, T.P., Storey, R.D., Müller, R.D., Gahagan, L.A., 2002. Kerguelen hotspot magma output since 130 Ma. Journal of Petrology 43, 1121–1140.

Christidis, G.E., Huff, W.D., 2009. Geological aspects and genesis of bentonites. Elements 5, 93–98.

Das Gupta, S., 1996. Bentonite deposits intercalated with Rajmahal volcanic rocks of eastern India. In: Ghose, N.C., Kent, R.W., Saunders, A.D. (Eds.), Mesozoic Magmatism of Eastern Margin of India. Journal of Southeast Asian Earth Sciences 13, pp. 133–137.

Desa, M.A., Ramana, M.V., Ramprasad, T., Anuradha, M., Lall, M.V., Kumar, B.J.P., 2013. Geophysical signatures over and around the northern segment of the 85°E Ridge, Mahanadi offshore, eastern continental margin of India and their tectonic implications. Journal of Asian Earth Science 73, 460–472.

Deshmukh, S.S., 1964. Geology of the area around Taljhari and Berhait, Rajmahal hills, Santhal Paraganas, Bihar. Report 22nd International Geological Congress, Part 7, pp. 61–84.

Fisher, R.V., Schmincke, H.U., 1984. Pyroclastic Rocks. Springer, Berlin, 372 pp.

Ghatak, A., Basu, A.R., 2011. The Sylhet Traps: Vestiges of the Kerguelen plume in northeastern India. Earth and Planetary Science Letters 308, 52–64.

Ghatak, A., Basu, A.R., 2013. Isotopic and trace element geochemistry of alkalic–mafic–ultramafic–carbonatitic complexes and flood basalts in NE India: origin in a heterogeneous Kerguelen plume. Geochimica et Cosmochimica Acta 115, 46–72.

Ghose, N.C., 1983. Geology, Tectonics and Evolution of the Chhotanagpur Granite Gneiss Complex, Eastern India. Recent Research in Geology 10. Hindustan Publishing Co., Delhi, pp. 211–247.

Ghose, N.C., Singh, S.P., Singh, R.N., Mukherjee, D., 1996. Flow stratigraphy of a selected sections of Rajmahal basalts, eastern India. In: Ghose, N.C., Kent, R.W., Saunders, A.D. (Eds.), Mesozoic Magmatism of the Eastern Margin of India. Journal of Southeast Asian Earth Sciences 13, pp. 83–93.

Ghose, N.C., Mukherjee, D., 2000. Chotanagpur Gneiss-Granulite Complex, Eastern India – A Kaleidoscope of Global Events. Geology and Mineral Resources of Bihar and Jharkhand, Institute of Geo-exploration, Monograph 2, pp. 33–58.

Ghose, N.C., Kent, R.W., 2003. The Rajmahal basalts: a review of their geology, composition and petrogenesis. Geological Society of India, Memoir 53, 167–196.

Grove, T.L., Baker, M.B., 1984. Phase equilibrium controls on the tholeiitics versus calc-alkaline differentiation trends. Journal of Geophysical Research 89 (B5), 3253–3274.

Ingle, S., Weis, D., Frey, F.A., 2002. Indian continental crust recovered from Elan Bank, Kerguelen Plateau (ODP Leg 183, Site 1137). Journal of Petrology 43, 1241–1257.

Jay, A.E., Widdowson, M., 2008. Stratigraphy, structure and volcanology of the SE Deccan continental flood basalt province: implications for eruptive extent and volumes. Journal of Geological Society of London 165, 177–188.

Jerram, D.A., Widdowson, M., 2005. The anatomy of continental flood basalt provinces: geological constraints on the processes and products of flood basalt volcanism. Lithos 79, 385–405.

Keller, G., Adatte, T., Gardin, S., Bartolini, A., Bajpai, S., 2008. Main Deccan volcanism phase ends near the K-T boundary: evidence from the Krishna-Godavari Basin, SE India. Earth and Planetary Science Letters 268, 293–311.

Kent, R.W., Saunders, A.D., Storey, M., Ghose, N.C., 1996. Petrology of Early Cretaceous flood basalts and dykes along the rifted volcanic margin of eastern India. In: Ghose, N.C., Kent, R.W., Saunders, A.D. (Eds.), Mesozoic Magmatism of the Eastern Margin of India, Journal of Southeast Asian Earth Sciences, 13, pp. 95–111.

Kent, R.W., Saunders, A.D., Kempton, P.D., Ghose, N.C., 1997. Rajmahal basalts, Eastern India: mantle sources and melt distribution at a volcanic rifted margin. In: Mahoney, J.J., Coffin, M.F. (Eds.), Large Igneous Provinces: Continental, Oceanic, and Planetary Flood Volcanism, American Geophysical Union, Geophysical Monograph, 100, pp. 145–182.

Kent, R.W., Pringle, M.S., Muller, R.D., Saunders, A.D., Ghose, N.C., 2002. $^{40}Ar/^{39}Ar$ geochronology of the Rajmahal basalts, India and their relationship to the Kerguelen Plateau. Journal of Petrology 43, 1141–1153.

Klootwijk, C.T., 1971. Paleomagnetism of Upper Gondwana Rajmahal traps, north-east India. Tectonophysics 12, 449–467.

Kshirsagar, P.V., Sheth, H.C., Shaikh, B., 2011. Mafic alkalic magmatism in central Kachchh, India: a monogenetic volcanic field in the northwestern Deccan Traps. Bulletin of Volcanology 73, 595–612.

Le Bas, M.J., Le Maitre, R.W., Streckeisen, A., Zanettin, B., 1986. A chemical classification of volcanic rocks based on the total alkali-silica diagram. Journal of Petrology 27, 745–750.

Mahadevan, T.M., 2002. Geology of Bihar and Jharkhand. Geological Society of India, Bangalore, 563 pp.

Marsh, J.S., Hooper, P.R., Rehacek, J., Duncan, R.A., Duncan, A.R., 1997. Stratigraphy and age of Karoo Basalts of Lesotho and implications for correlations within the Karoo Igneous Province. In: Mahoney, J.J., Coffin, M.F. (Eds.), Large Igneous Provinces: Continental, Oceanic, and Planetary Flood Volcanism, Geophysical Monograph, 100, pp. 247–272.

Mahoney, J.J., Coffin, M.F. (Eds.), 1997. Large Igneous Provinces: Continental Oceanic, and Planetary Flood Volcanism. American Geophysical Union, Geophysical Monograph, 100, 438 pp.

McDonough, W.F., Sun, S.-S., 1995. The composition of the earth. Chemical Geology 120, 223–253.

McDougall, I., McElhinny, M.W., 1970. The Rajmahal traps of India, K-Ar ages and paleomagnetism. Earth and Planetary Science Letters 9, 373–378.

Mohr, B.A.R., Wähnert, V., Lazarus, D., 2002. Mid-Cretaceous paleobotany and palynology of the central Kerguelen Plateau, southern Indian Ocean (ODP Leg 183, Site 1138). In: Frey, F.A., Coffin, M.F., Wallace, P.J., Quilty, P.G. (Eds.), Proceedings of ODP (Ocean Drilling Program) Scientific Results, vol. 183, pp. 1–39.

Mukhopadhyay, M., Verma, R.K., Ashraf, M.H., 1986. Gravity field and structures of the Rajmahal Hills: examples of the Paleo-Mesozoic continental margin in eastern India. Tectonophysics 131, 353–367.

Pascoe, E.H., 1975. A Manual of Geology of India and Burma. Government of India Publication, New Delhi, pp. 1345–2130.

Poornachandra Rao, G.V.S., Mallikharjuna Rao, J., Subba Rao, M.V., 1996. Palaeomagnetic and geochemical characteristic of the Rajmahal traps, eastern India. In: Ghose, N.C., Kent, R.W., Saunders, A.D. (Eds.), Mesozoic Magmatism of Eastern Margin of India, Journal of Southeast Asian Earth Sciences 13, pp. 113–122.

Putirka, K.D., 2008. Thermometers and barometers for volcanic systems. In: Putirka, K.D., Tepley, F. (Eds.), Reviews in Mineralogy and Geochemistry, Mineralogical Society of America, 69, pp. 61–120.

Raja Rao, R.C.S., Purushottam, A., 1963. Pitchstone flows in the Rajmahal Hills, Santhal Paraganas, Bihar. Geological Survey of India, Records 91, 341–348.

Rankama, K., Sahama, Th.G., 1964. Geochemistry. The University of Chicago Press, Chicago and London, 912 pp.

Ratheesh-Kumar, R.T., Windley, B.F., Sajeev, K., 2014. Tectonic inheritance of the Indian Shield: new insights from its elastic thickness structure. Tectonophysics 615–616, 40–52.

Ray, J.S., Pattanayak, S.K., Pande, K., 2005. Rapid emplacement of the Kerguelen plume-related Sylhet Traps, eastern India: evidence from $^{40}Ar-^{39}Ar$ geochronology. Geophysical Research Letters 32, 1–4.

Roy Gupta, T.L., 1931. A short note on some intertrappean rocks from the Rajmahal hills, Bihar. Quarterly Journal of Geology, Mining and Metallurgy Society of India 2, 29–36.

Sarbadhikari, T.R., 1968. Petrology of the northeastern portion of the Rajmahal traps. Quarterly Journal of Geology, Mining and Metallurgy Society of India 60, 151–171.

Sarkar, S.S., Nag, S.K., Basu Mallik, S., 1989. The origin of andesites from Rajmahal traps, eastern India: a quantitative evaluation of a fractional crystallization model. Journal of Volcanology and Geothermal Research 37, 365–378.

Sengupta, S., 1966. Geological and geophysical studies in western part of Bengal basin, India. American Association of Petroleum Geology, Bulletin 50, 1001–1017.

Sengupta, S., 1988. Upper Gondwana stratigraphy and palaeobotany of Rajmahal hills, Bihar. Memoir Geological Survey of India, Palaeontologica Indica 88, 185.

Sherwood, G.J., Basu Mallik, S., 1996. A palaeomagnetic and rock magnetic study of the northern Rajmahal Volcanics, Bihar, India. In: Ghose, N.C., Kent, R.W., Saunders, A.D. (Eds.), Mesozoic Magmatism of Eastern Margin of India. Journal of Southeast Asian Earth Sciences 13, pp. 123–131.

Sheth, H.C., Choudhary, A.K., Bhattacharyya, S., Cucciniello, C., Laishram, R., Gurav, T., 2011. The Chogat-Chamardi subvolcanic complex, Saurashtra, northwestern Deccan Traps: geology, petrochemistry, and petrogenetic evolution. Journal of Asian Earth Sciences 41, 307–324.

Singh, A.P., Kumar, N., Singh, B., 2004. Magmatic underplating beneath the Rajmahal Trap: gravity signature and derived 3D configuration. Proceedings of Indian Academy of Science (Earth Planetary Sciences) 113, 759–769.

Storey, M., Kent, R.W., Saunders, A.D., Hergt, J., Salters, V.J.M., Whitechurch, H., Sevigny, J.H., Thirlwall, N.F., Leat, P., Ghose, N.C., Gifford, M., 1992. Lower Cretaceous rocks on continental margins and their relationship to the Kerguelen plateau. Proceedings of ODP (Ocean Drilling Program), Scientific Results 120, 33–53.

Talukdar, S.C., Murthy, M.V.N., 1970. The Sylhet traps, their tectonic history and their bearing on problems of Indian flood basalt provinces. Bulletin Volcanologique 35, 602–618.

Tripathi, A., 2008. Palynochronology of Lower Cretaceous volcano-sedimentary succession of the Rajmahal Formation in the Rajmahal Basin, India. Cretaceous Research 29, 913–924.

Tuttle, O.F., Bowen, N.L., 1958. Origin of granite in the light of experimental studies in the system $NaAlSi_3O_8$-$KAlSi_3O_8$-SiO_2-H_2O. Geological Society of America, Memoir 74, 153.

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Vijaya, 2009. Palynofloral changes in the Upper Paleozoic and Mesozoic of the Deocha-Pachami area, Birbhum coalfield, West Bengal, India. Science in China, Series D–Earth Science 52 (12), 1932–1952.

Vijaya, Bhattacharji, T.K., 2002. An Early Cretaceous age for Rajmahal Traps, Panagarh area, West Bengal: palynological evidence. Cretaceous Research 23, 789–805.

White, J.D.L., Houghton, B.F., 2006. Primary volcaniclastics rocks. Geology 34, 677–680.

White, J.D.L., Bryan, S.E., Ross, P.-S., Self, S., Thordarson, T., 2009. Physical volcanology of continental large igneous provinces: update and review. In: Thordarson, T., Self, S., Larsen, G., Rowland, S.K., Hoskuldsson, A. (Eds.), Studies in Volcanology: The Legacy of George Walker. Geological Society of London, pp. 291–321.

Winkler, H.G.F., Ghose, N.C., 1973. Further data on eutectics in the system Quartz-Orthoclase-Anorthite-Water. Neues Jahrbuch Mineralogie Monatsheft 11, 481–484.